REVIEW ARTICLES

Journal of Oil Palm Research Vol. 37 (3) September 2025 p. 377-396
DOI: https://doi.org/10.21894/jopr.2024.0018

DISCOVERING THE GLOBAL LANDSCAPE OF WOOD PRESERVATIVES

NUR AZREENA, I[1]*; ZAWAWI, I[1] and NOORSHAMSIANA, A W[1]

ABSTRACT

Wood is a precious natural resource used in many human activities, including construction and furnishing of building interiors. However, wood decomposes due to a variety of wood decay fungi species, including brown rot, white rot or soft rot fungi, inorganic elements, moisture and weathering. Therefore, a variety of wood preservation techniques have been developed to lengthen the service life of wood, lowering replacement costs and enabling wood to be used more effectively in numerous applications. A bibliometric analysis of 4,153 Scopus articles on wood preservatives, including biocide use of wood vinegar and oil palm wood vinegar, was conducted. The data was visualised using VOSviewer, analysed using Harzing's Publish or Perish and evaluated in Microsoft Excel for frequency of occurrences. This article analysed wood preservative research and development over time by categorising article by title, country of origin, publishing institution, and publication citation patterns. This review highlighted the most important research participants and suggested that wood preservatives are extensively used and have had a significant impact on the number of articles published in regions such as Europe and Asia. These findings extend to emerging patterns and issues in terms of publication frequency, journal impact factor, collaborative patterns and research components, which supplement the scarce global wood preservative trends literature.

Keywords: bibliometric, decay, VOSviewer, wood, wood preservatives.

Received: 9 August 2023; **Accepted:** 29 December 2023; **Published online:** 21 February 2024.

INTRODUCTION

Wood is a significant biomaterial due to its durability and versatility (Pędzik *et al.*, 2021). Its flexibility has resulted in its widespread use in fields as diverse as architecture, interior design, transportation and decoration. Its adaptability has led to its extensive use in a wide variety of structural, architectural, aesthetic, and decorative applications, as well as in automobiles and ships (Lazim *et al.*, 2020). This has led to a rise in demand for its consumption, which is largely attributable to the increase in global population, despite resulting in a corresponding decline in forest-covered regions around the world (Chen *et al.*, 2020).

According to the wood products global market report, 2022 forecasts, the value of the global wood products market will increase from USD696.78 billion in 2022 to USD748.01 billion in 2023, at a compound annual growth rate (CAGR) of 7.4%. In addition, the Russia-Ukraine war affected the chances of the global economy recovering from the COVID-19 pandemic. The war between these two nations has resulted in economic sanctions on multiple nations, a spike in commodity prices, and supply chain disruptions, resulting in inflation across goods and services and affecting many global markets. Despite that, the wood products market is projected to reach USD964.41 billion by 2027 at a CAGR of 6.6% (The Business Research Company, 2022).

In contrast to plastics, wood has significant limitations such as dimensional instability and lack of durability due to high carbohydrate content in parenchymal cells (Mohamad Amini *et al.*, 2019; Zhang *et al.*, 2018). Furthermore, since wood contains cell walls, porous and hygroscopic by nature, it is extremely vulnerable to biological degradation by termites, fungi and insects (Sun *et al.*, 2022; Yan *et al.*, 2021). As a result, there will be economic losses and negative effects on the environment. Biodegradable

[1] Malaysian Palm Oil Board,
6, Persiaran Institusi, Bandar Baru Bangi,
43000 Kajang, Selangor, Malaysia.

* *Corresponding author e-mail: azreena@mpob.gov.my*

wood, an engineered wood product manufactured from natural wood fibres and biodegradable resins has a low carbon footprint and is recyclable besides its biodegradability properties (Cai *et al.*, 2020). Wood-plastic composites (WPCs) are a greener option to traditional wood products like lumber and plywood, which have a negative effect on the environment and contribute to deforestation (Lee *et al.*, 2020). One of the main advantages of biodegradable wood in the furniture industry is its longevity. Due to its strength and resistance to deterioration, it is an ideal furniture as it will not be damaged by moisture, fungus, or insects (Pour *et al.*, 2021).

The cell wall components of wood are composed of hemicelluloses, cellulose, and lignin. Meanwhile, parenchyma cells serve primarily as storage organelles for macromolecules like starch, pectin, simple sugars, fatty acids, and proteins. They are responsible for the structural qualities of wood, but microorganisms, particularly fungi and bacteria, can rapidly degrade them (Martín & López, 2023). Under certain environmental circumstances, such as moisture content above 20%, oxygen availability and a temperature range of 15°C-45°C, wood becomes susceptible to fungal infestation (Broda, 2020). Traditionally, wood-decay fungi have been classified into three main groups; white-rot, brown-rot and soft-rot fungi. The white-rot basidiomycetes are capable of breaking down the cell wall (polysaccharides and lignin). It can either degrade all wood components at once or specialise in degrading either lignin or polysaccharides. One of the most harmful types of wood-decay is caused by the brown-rot fungi, which is also a basidiomycete, the second category of wood-decaying organisms that can metabolise cell wall polysaccharides. Additionally, the third category of wood-rotting fungi consists of the ascomycete soft-rot fungi, which can degrade both cell wall polysaccharides and lignin (Nadali *et al.*, 2021). Therefore, it is necessary to lessen wood's hygroscopicity, enhance its dimensional stability and avoid attacks from biological organisms that cause decay by using wood preservatives.

Wood preservatives are chemical substances used in various wood preservation treatments to protect wood from insects and fungi. The different types of preservatives, such as oil-borne, water-borne and organic solvent-borne preservatives, can be identified by the solvents in which they are dissolved. Different characteristics and chemical properties distinguish each preservative (Teng *et al.*, 2018). Oil-borne preservatives, which include pentachlorophenol (PCP) and creosote, are generally referred to as heavy-duty organic preservatives. These preservatives can withstand high temperatures and chemicals without breaking down, and they are also resistant to leaching since they are insoluble in water (Khademibami & Bobadilha, 2022). However, these oil-based preservatives make the treated wood appear dark brown and produce a strong odour. They typically cause harm to both people and the environment. Thus, oil-borne preservatives are often only used in outdoor applications, such as poles and train lines where there is no risk to human contact and limited effects on the environment (Ahmed *et al.*, 2020).

Typically, water-borne preservatives are among the least expensive options available to consumers, and this may be their greatest advantage. Nevertheless, their biggest drawback is that they frequently cause the treated wood to swell if it is already porous, as the water in the preservatives is absorbed into the wood. Many water-based preservatives, such as chromated copper arsenate (CCA), alkaline copper quaternary and copper azole, have copper or a copper-based molecule as their primary active ingredient (Liu *et al.*, 2021). The primary chemical compound used in producing a water-borne preservative is CCA. However, many of them have been restricted from use due to environmental and health concerns due to the presence of arsenic in CCA, which is toxic to aquatic life and can cause cancer in humans due to their being easily absorbed by the human body (Lin *et al.*, 2009), necessitating the development of substitute wood protection agents and techniques based on non-toxic natural products. Despite their effectiveness as fungicides, it was recently discovered that these chemical compounds are carcinogenic and contain immunotoxins that can cause skin cancer (Smith, 2020).

Despite their usefulness in extending the life of wood products, wood preservatives can have various environmental impacts. Certain wood preservatives can leach into the soil and water, causing contamination. Both aquatic and terrestrial ecosystems may be harmed by this contamination (Chang *et al.*, 2015). Wood preservatives can potentially seep into groundwater, thereby having a harmful effect on both human health and aquatic life. They may also be introduced into nearby streams, rivers, and other water bodies, which can be toxic to aquatic life, harming fish, insects and other organisms in the ecosystem (Engwall *et al.*, 1999). In addition, airborne particles and volatile organic compounds (VOCs) may be generated while applying wood preservatives, which could have an impact on air quality, have implications for human health and may contribute to smog formation (Bahmani & Schmidt, 2018).

A study was conducted by Lebow *et al.* (2002) to determine the CCA, ammoniacal copper zinc arsenate (ACZA), ammoniacal copper quat (ACQ-B) and copper dimethyldithiocarbamate (CDDC) treated wood leaching into surrounding water and soil, as well as their effects to the environment. Based on their study, the soil and sediments in the wetland areas were contaminated by these four different types of treated wood. In general, higher concentrations were found in soil due to the greater mobility of these leached components compared to sediments. Meanwhile, the levels of preservative components found in sediments did not appear to have any negative effects on the number or variety of aquatic invertebrates. Furthermore, in Brazil, traditional treatments based on CCA and chromated copper borate (CCB) are the most utilised. Even though this type of treatment causes undesirable wood colour changes, and presents risks to the environment and human health, they have a significantly better performance from wood treated with alternative copper-based preservatives than that of CCA-treated wood (Hingston *et al.*, 2001).

Despite its purpose in preserving wood products, the usage of wood preservatives raises various safety concerns. Many wood preservatives contain toxic chemicals, such as arsenic, creosote, PCP and CCA (Bayatkashkoli *et al.*, 2017). Workers involved in the manufacturing, application, or disposal of treated wood may be exposed to these toxic chemicals, and prolonged or high-level exposure can lead to serious health issues. Additionally, wood preservatives can cause skin and eye irritation when they come in contact. Skin contact with these substances over time may cause dermatitis and other skin problems. Redness, discomfort, and even permanent damage to the eyes can happen from accidental eye contact (Broda, 2020).

Furthermore, breathing in dust and VOCs while applying wood preservatives can irritate the respiratory system and cause breathing problems. This could lead to mild respiratory symptoms like coughing or more serious cases like wheezing (Aguayo *et al.*, 2022). Chemicals used as wood preservatives can be toxic and, in extreme situations, cause poisoning if consumed or inhaled. It is essential to follow safety protocols and use appropriate protective gear and ventilation to reduce the risk of exposure (Jin *et al.*, 2020). Besides, they must educate and remain up-to-date on pertinent rules and guidelines to maintain regulatory compliance and reduce safety risks. They must also adhere to disposal regulations and utilise approved disposal methods for treated wood products (Adhikari & Ozarska, 2018). Moreover, there are health and safety concerns associated with the final disposal of treated wood products. Improper disposal techniques for the treated wood may lead to groundwater contamination while burning it will emit dangerous chemicals into the atmosphere. Therefore, to reduce these risks, proper disposal procedures are required. Rules and regulations aimed at safeguarding the environment and public health may apply to the use of specific wood preservatives (Meena, 2022). To address these safety concerns, the use of proper personal protective equipment (PPE) is crucial when handling wood preservatives (Bernard Effah, 2015).

Future directions in wood preservatives will likely be affected by environmental concerns, regulatory changes, and technological advances (Freeman *et al.*, 2003). To increase the efficiency of wood preservatives, nanoscale additives and coatings are being developed. These advances in technology can improve the effectiveness of wood preservatives, making them more resistant to decay and insect infestations (Pařil *et al.*, 2017). Alternative wood preservation techniques like heat treatment, acetylation, and furfurylation are all being investigated by researchers. These treatments modify the wood's properties to make it naturally resistant to decay and insects. By altering its natural characteristics, these treatments provide resistance against insects and rot (Sandberg *et al.*, 2017). This will encourage the industry to develop and implement more environmentally friendly solutions. Technological advancements in testing methodologies will enable manufacturers to better analyse the durability of treated wood, resulting in the development of more effective preservation systems. The trend of procuring wood in a sustainable and accountable manner will continue to increase. This includes encouraging the use of recycled wood and utilising only certified wood from sustainably managed forests. As consumers become more aware of the impact of their decisions on the environment, there will be a greater emphasis on educating the public about the advantages of using preserved wood and the proper disposal of treated wood products. These trends reflect ongoing efforts to maintain a balance between the preservation of wood products and environmental and safety concerns. It is crucial for the wood preservation industry to adapt and innovate in response to these changing trends.

Various efforts, including the use of alternative, eco-friendly wood preservatives, improved application and disposal techniques, and the establishment of treated wood recycling programmes, can be implemented to minimise these environmental impacts (Cai *et al.*, 2020). To eliminate the use of toxic metallic preservatives, organic solvent-borne preservatives like triazoles and pyrethroids have been developed. These types of preservatives are non-volatile, odourless, non-toxic and hypoallergenic; thus, they are utilised for indoor applications (Petrič *et al.*, 2000). Combining antioxidants and metal chelators with organic solvent-borne preservatives can increase the efficacy and water dispensability of the biocides. However, the relatively high price of organic solvents and emulsifiers restricts their use, so the majority of relevant industrial facilities continue to support water-based formulations (Broda, 2020).

Currently, a wide range of techniques are being researched in depth for eco-friendly wood protection that are naturally formed, such as wood extractives, plant extracts, or biomass (Teacă *et al*., 2019). Since wood-degrading fungi can only grow in the presence of water, it is best to prevent their growth by keeping the wood dry with hydrophobic materials like plant oils and natural resins (Calegari *et al*., 2017). Wood can be preserved in another way by embedding organic substances with biocidal properties into its structure. The more cutting-edge approach uses biological control agents, which are microscopic organisms such as other fungi and bacteria that compete with wood-decaying fungi (Barbero-lópez *et al*., 2021).

Additionally, wood vinegar (WV) is a liquid by-product of biomass pyrolysis used to produce biofuels and biochar through the downstream processes of condensation and gas/vapour separation. WV typically consists of over 80% water and a wide variety of organic compounds, including acids, phenols and alcohols. Its organic components have been found to affect microbial activities, making it useful as an antibacterial agent, pesticide, and antioxidant (Zhang *et al*., 2019). For instance, Desvita *et al.* (2022) aimed to determine the antimicrobial activity of cocoa pod shell-derived WV. WV was found to be effective in preventing the spread of two potentially harmful microorganisms, *Candida albicans* and *Aspergillus niger*. The diameter of the microbial growth inhibition zone increased with WV concentration, suggesting that WV made from cocoa pod shells has antimicrobial characteristics. Jung *et al.* (2016) investigated the fungal inhibitory effect of wood blocks with WV. According to the findings, a concentration of 0.30 g/mL of WV protected the wood against white rot and brown rot fungi. Since WV inhibited the growth and spread of mycelia, it preserved the wood from deterioration by preventing cell wall erosion and thinning. Furthermore, the degree of weight loss reflected how effectively the body repelled the fungal infection.

Oil palm WV, produced by carbonising oil palm lignocellulosic materials (*e.g*., oil palm trunk and oil palm kernel shell), primarily comprises phenolic and acetic acid compounds that exhibit significant antifungal properties (Ariffin *et al*., 2017). For years, special attention has been given to this biomass pyrolysis product to increase the economic viability while contributing to the reduction of the environmental pollution arising from oil palm lignocellulosic by-product accumulation and open field burning (Oramahi *et al*., 2019). Lee *et al*. (2022) proved that WV which is also known as pyroligneous acid could be used as a wood preservative for the renewable timber species that are currently in demand despite their lower durability against biodegradation. In the study, rubberwood was protected from decay and mould when treated with 50% rubberwood wood vinegar (RWWV) and 30% oil palm trunk wood vinegar (OPTWV). Consequently, OPTWV indicated better biological durability compared to RWWV. Therefore, additional research confirming the new role of WV as an antibiological wood preservative will elevate the green value and serviceability of one of the woods.

Despite the increasing popularity of sustainable wood preservatives and a wide range of potential uses, there is a significant research gap in the form of insufficient systematic and quantitative analyses. Thus, our primary objective is to bridge this gap by conducting a comprehensive bibliometric analysis, which will provide a holistic view of the wood preservatives research landscape. Bibliometric analysis is extensively used since it permits precise measurement and analysis of the articles indexed in an investigative database (Donthu *et al*., 2021; Moral-muñoz *et al*., 2020). Earlier, Li *et al*. (2022) conducted a bibliometric review entitled "Wood decay fungi: An analysis of worldwide research" by using the Web of Science (WOS) Core Collection to perform a literature review. This study summarised the current research landscape, highlighted leading research centres, journals, authors and academic communities and elucidated the most imperative research questions search from 1913-2020. This review presented the current state of research, identified significant institutions, journals, authors and academic communities and elucidated the most relevant areas of current research. Since then, research on wood preservatives has advanced substantially, and it is essential to stay updated on the most recent literary developments. This study conducted a bibliometric analysis of published wood preservatives research from 1909-2024 to determine the breadth and depth of scholarly work on wood preservatives. Additionally, three fundamental research questions were addressed. First, how is the study of wood preservatives evolving and progressing? Second, what are the most prevalent research topics concerning wood preservatives? Third, who and what are the leading researchers and institutions in terms of wood preservative publication output?

In the next sections of this study, the research methods, evolution, and distribution of published studies per year, sources, document categories and document languages were detailed. Keyword frequency and co-occurrences, among the most prominent subjects of interest to scholars, were also emphasised.

MATERIALS AND METHODS

In this work, the assessment of wood preservatives in wood deterioration research was the centre of the research complement with WV and oil palm

WV as the applicable wood preservatives. These bibliometric study materials were analysed using the Scopus database (Muhuri *et al.*, 2019). There was more than 27,100 active titles in Scopus, 7,000 publishers, 84 million documents, 17.6 million author profiles, 249,000 books, 80,000 institutional profiles and 1.8 billion citations. This database was chosen because of its comprehensive coverage of scientific research around the world and its status as one of the most important data repositories in the field (Mansour *et al.*, 2022). Scopus is therefore recommended as a good database for extracting content relating to the topic of this study.

Keywords were used to identify the relevant documents. 'Wood preservatives', 'wood vinegar' and 'oil palm wood vinegar' were used as keywords to locate article titles and abstracts in the Scopus database. This search was conducted on 17 March 2023, using specified documents published from 1909 until 2024. A total of 4,162 new articles appeared as a result. After the documents were further screened, and nine types of erratum documents were omitted, the final number of Scopus-retrieved documents was down to 4,153. In addition, the standard protocol of the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement was applied to the review of articles, as depicted in a flowchart (*Figure 1*). Thus, this review gained conformance by adhering to the PRISMA protocol's detailed procedures (Maier, 2021).

The number of publications indexed by the repository was determined and analysed through bibliometric analysis for this study (Moral-muñoz *et al.*, 2020). This analysis, which is based on statistical data, is used in archives and records to identify publication trends within a particular field or body of literature (Van Eck & Waltman, 2010). To provide comprehensive answers to the research questions, a number of methods were used to collect data. The frequency and percentage of each publication were calculated using Microsoft Excel 2019 along with the necessary graphs and charts. The bibliometric linkages and visualisation were generated using VOSviewer (version 1.6.18), and the citation metrics were calculated using Harzing's Publish and Perish software version 8.6.4198.8332.

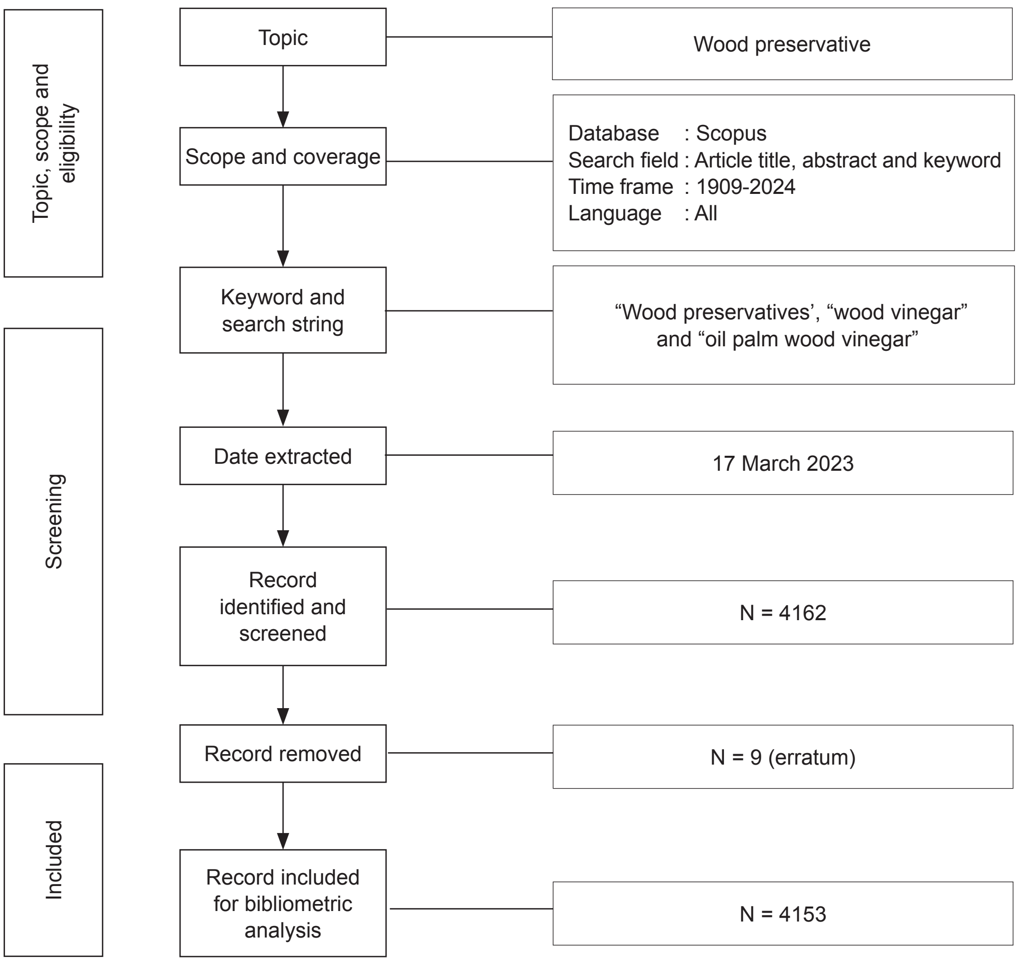

Figure 1. *Schematic in accordance with the PRISMA declaration.*

RESULTS AND DISCUSSION

The Advancement and Development of Wood Preservatives Research

To respond to the first research question (How the study of wood preservatives is developing and moving forward?), the following discussions were included: (a) Annual number of published studies; (b) document types; (c) source types; and (d) document languages.

Annual number of published studies. Detailed statistics on annual publications of wood preservatives (from 1909 to 2024), wood vinegar (from 1993-2023) and oil palm wood vinegar (from 2017-2023) research are shown in *Figure 2*. The highest number of publications was received for 2020 (161, wood preservatives), 2022 (60, wood vinegar) and 2023 (3, oil palm wood vinegar). Less than 100 articles on wood preservatives were documented in the Scopus database for articles published between 1929 and 2004, while all articles on wood vinegar and oil palm wood vinegar were less than 100. The number of publications varied from 2005-2022, due to the increased interest in wood preservatives. This analysis was done immediately at the end of March 2023, even though there were only 30 articles up to that time of the year. The total quantity of documents for the year had yet to be disclosed. The Scopus database also noted that a journal had publications arranged up to 2024 and the number of documents released in prior years 1909-1971 was less than 20. Total publications were rising, although with a fluctuating tendency. The annual total document revealed the language of documents published in wood preservative publications, the types of documents, the most popular source titles, and the sources for wood preservative research.

Document types. The document types were differentiated into 12 different categories (*Table 1*). More than half of the publications from those three titles (wood preservative, wood vinegar and oil palm wood vinegar) were categorised as articles, accounting for 2,943, 378 and 5 (79.18%, 88.11% and 55.56%), conference papers 374, 35 and 3 (10.06%, 8.16% and 33.33%), and reviews accounting 206, 8 and 0 (5.54%, 1.86% and 0.00%). Other forms of publications, such as book chapters, notes, books, short surveys, letters, conference reviews and reports made up less than 5% of the total publications. The least frequent document type, accounting for 1 document, was notes and conference reviews for the wood vinegar title.

Sources types. Research articles were classified into seven primary source types, with journal documents comprised of 3,043, 383, and six documents (81.87%, 89.28% and 66.67%) being the largest source type, while conference proceedings with 237, 27 and 3 documents, respectively (6.38%, 6.29% and 33.33%) coming in second. Trade journals, which accounted for 5.38% and 0.70% (200 and 3 articles) of all publications, also contributed significantly (*Table 2*). Articles that made up less than 5.00% of total publications were books (n = 115 and 3, 3.09% and 0.70%), book series (n = 109 and 12, 2.93% and 2.80%), reports (n = 11, 0.30%), and undefined (n = 2 and

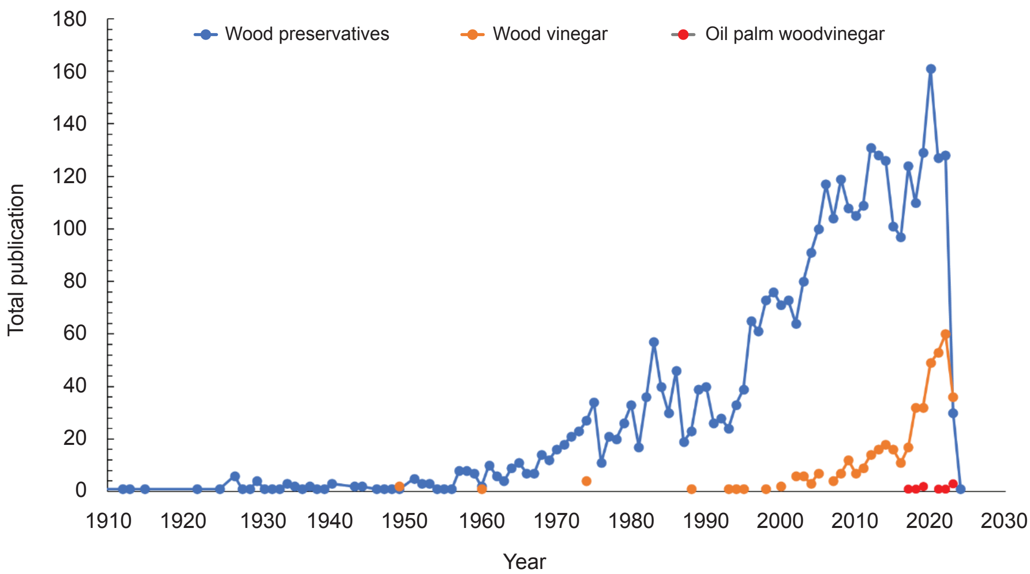

Figure 2. Annual totals for publications.

TABLE 1. TYPES OF DOCUMENTS

Types of documents	Total publications			(%)		
	1	2	3	1	2	3
Articles	2,943	378	5	79.18	88.11	55.56
Conference papers	374	35	3	10.06	8.16	33.33
Reviews	206	8	0	5.54	1.86	0
Book chapters	108	3	0	2.91	0.7	0
Notes	22	1	0	0.59	0.23	0
Books	14	0	0	0.38	0	0
Short surveys	12	0	0	0.32	0	0
Letters	11	0	0	0.30	0	0
Conference reviews	10	1	0	0.27	0.23	0
Reports	9	0	0	0.24	0	0
Erratum	5	3	1	0.13	0.70	11.11
Editorial	3	14	0	0.08	0	0

Note: 1 - wood preservative; 2 - wood vinegar; 3 - oil palm wood vinegar.

TABLE 2. SOURCES TYPE

Sources types	Total publication			(%)		
	1	2	3	1	2	3
Journals	3,043	383	6	81.87	89.28	66.67
Conference proceedings	237	27	3	6.38	6.29	33.33
Trade journals	200	3	0	5.38	0.7	0.00
Books	115	3	0	3.09	0.7	0.00
Book series	109	12	0	2.93	2.8	0.00
Reports	11	0	0	0.30	0.00	0.00
Undefined	2	1	0	0.05	0.23	0.00

Note: 1 - wood preservative; 2 - wood vinegar; 3 - oil palm wood vinegar.

1.0, 0.05% and 0.23%). Once the document and source types were established, the most frequently published language was analysed to determine its prevalence.

Languages of documents. Wood preservatives, WV and oil palm WV research articles were produced in a total of 25, six and single languages, respectively, with English being the most prominent (82.00%-100.00%) followed by Chinese (15.12%) and German (5.78%) (*Figure 3*). The remainder of the materials were translated into other languages namely Portuguese, Japanese, Korean, Spanish, French, Turkish, Polish, Russian, Finnish, Croatian, Dutch, Italian, Danish, Estonian, Moldavian, Moldovan, Persian, Romanian, Serbian, Slovak, Swedish and Ukrainian. After determining the current language trends, the subject area was the final identifier of the present trend.

Key areas of wood preservative research. The second research question was to identify the most prevalent themes in wood preservatives research in terms of (a) major subject areas, and (b) keyword frequency.

Subject area. Documents were categorised according to their subject area (*Table 3*) in which it was found that materials science accounted for more than 37.07% (n = 1,378) of the total articles, and agricultural and biological Sciences accounted for a considerable proportion (n = 1362; 36.64%) while less than 30.00% of all publications were in the fields of chemical engineering, chemistry, engineering, and environmental science. Meanwhile, biochemistry, computer science, earth and planetary sciences, energy, immunology and microbiology, medicine, pharmacology, toxicology and pharmaceutics, physics and astronomy, and social sciences, accounted for less than 10.00% of total publications. Arts and humanities, business, management and accounting, decision sciences, dentistry, economics, econometrics and finance, health professions, mathematics, multidisciplinary, neuroscience, nursing, psychology and veterinary accounted for less than 1.00% of the total publications. After ascertaining the trend and influence of publications in wood preservatives research, the most frequently used keywords in wood preservatives studies were analysed.

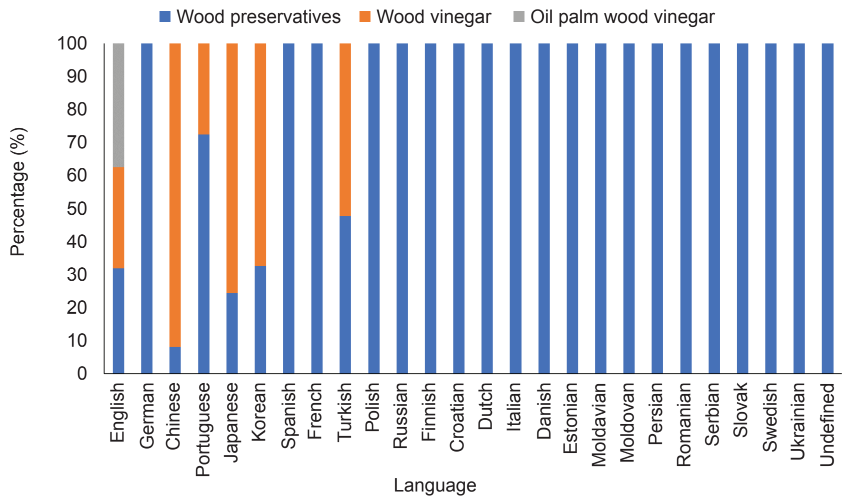

Figure 3. Languages used for publications.

TABLE 3. SUBJECT AREA

Subject areas	Total publications			(%)		
	1	2	3	1	2	3
Agricultural and biological sciences	1,362	170	2	36.64	39.63	22.22
Arts and humanities	23	0	0	0.62	0.00	0.00
Biochemistry, genetics and molecular biology	195	49	1	5.25	11.42	11.11
Business, management and accounting	34	4	0	0.91	0.93	0.00
Chemical engineering	401	0	0	10.79	0.00	0.00
Chemistry	506	54	0	13.61	12.59	0.00
Computer science	37	9	0	1.00	2.10	0.00
Decision sciences	1	0	0	0.03	0.00	0.00
Dentistry	2	0	0	0.05	0.00	0.00
Earth and planetary sciences	79	22	1	2.13	5.13	11.11
Economics, econometrics and finance	12	2	0	0.32	0.47	0.00
Energy	85	78	0	2.29	0.00	0.00
Engineering	767	62	1	20.63	0.00	11.11
Environmental sciences	890	119	2	23.94	0.00	22.22
Health professions	7	2	0	0.19	0.47	0.00
Immunology and microbiology	169	0	0	4.55	0.00	0.00
Materials science	1,378	34	2	37.07	7.93	22.22
Mathematics	17	3	0	0.46	0.70	0.00
Medicine	306	22	0	8.23	5.13	0.00
Multidisciplinary	36	13	2	0.97	3.03	22.22
Neuroscience	6	1	0	0.16	0.232	0.00
Nursing	4	2	0	0.11	0.47	0.00
Pharmacology, toxicology and pharmaceutics	125	0	0	3.36	0.00	0.00
Physics and astronomy	146	0	1	3.93	0.00	11.11
Psychology	1	0	0	0.03	0.00	0.00
Social sciences	38	7	0	1.02	1.63	0.00
Veterinary	16	11	0	0.43	2.56	0.00
Undefined	2	0	0	0.05	0.00	0.00

Note: 1- wood preservative; 2 - wood vinegar; 3 - oil palm wood vinegar.

Frequency of keywords. The fundamental concept of keyword analysis is that the author's keywords adequately reflect the article's subject area (Donthu *et al*., 2021). *Table 4* summarises 20 of the most frequently used keywords in wood preservatives, WV and oil palm WV studies. The data further revealed that wood preservation was the keyword most associated with wood preservatives (n = 1,071; 28.81%) followed by wood with 1,005 of total publications (27.04%). Other keywords that appeared more than 100 times were wood preservatives, article, protective coatings, copper, fungi, leaching, nonhuman, wood products, human, wood protecting agent, decay (organic), controlled study, timber, pentachlorophenol, priority journal, preservative, arsenic, chromated copper arsenate, chromium. After conducting a keywords analysis, the analysis on the title was made to further understand the prevalent themes.

Meanwhile, for WV and oil palm WV, there were the same keywords such as wood vinegar (257 and 5), acetic acid (163 and 2) and pyrolysis (100 and 2) were found in both search titles. This is speculated due to limited research and countries involved in oil palm wood vinegar production. *Figure 4* is a network visualisation of the most frequently used words and phrases. When two related keywords appear in the same article, it suggests that the two subjects are related (Nordin *et al*., 2022). To address the second research question, the keyword and co-occurrence analysis features of VOSviewer were utilised. VOSviewer is a software application for constructing and visualising bibliometric networks and mapping each article's assigned keywords. The colour, circle size, font size, and line thickness of connecting lines signify associations between other terms (Van Eck & Waltman, 2010).

Keywords that are frequently assigned the same colour are frequently clustered together. Based on the authors' keywords, 10 clusters including 323 items in the wood preservatives research were generated. The figure indicated that wood preservatives, PCP, biodegradation PCDD, indoor air, biocide, pesticide and nanotechnology have similar colours, indicating that these terms are closely related and frequently appear together. The primary keywords supplied in the search query were wood preservatives, article, protective coatings, copper and fungi were among the most often occurring (>10%) terms.

TABLE 4. TOP 20 KEYWORDS

No.	Keywords					
	Wood preservatives		WV		Oil palm WV	
1	Wood preservation	1,071	Wood vinegar	257	Wood vinegar	5
2	Wood	1,005	Acetic acid	163	Palm oil	3
3	Wood preservatives	643	Wood	133	Acetic acid	2
4	Article	577	Wood Vinegars	102	Pyrolysis	2
5	Protective coatings	576	Pyrolysis	100	Pyrolysis temperature	2
6	Copper	475	Vinegar	78	Agriculture	1
7	Fungi	420	Article	61	Anti Termites	1
8	Leaching	311	Biomass	60	Anti-fungal activity	1
9	Nonhuman	262	Charcoal	53	Antifungal activity	1
10	Wood Products	262	Nonhuman	44	Antioxidant enzymes	1
11	Human	232	Biochar	43	Antitermite activity	1
12	Wood protecting agent	231	Phenols	37	Bioactive compounds	1
13	Decay (Organic)	222	Unclassified drug	37	Biofilm	1
14	Controlled study	204	PH	36	Biological tests	1
15	Timber	201	Pyroligneous acid	35	Biostimulants	1
16	Pentachlorophenol	197	Controlled study	32	Carbendazim	1
17	Priority journal	197	Methanol	32	Central composite designs	1
18	Preservative	189	Carbonisation	28	Compost	1
19	Arsenic	188	Ketones	27	*Coptotermes formosanus*	1
20	Chromated copper arsenate	178	Animals	24	Drought stress	1

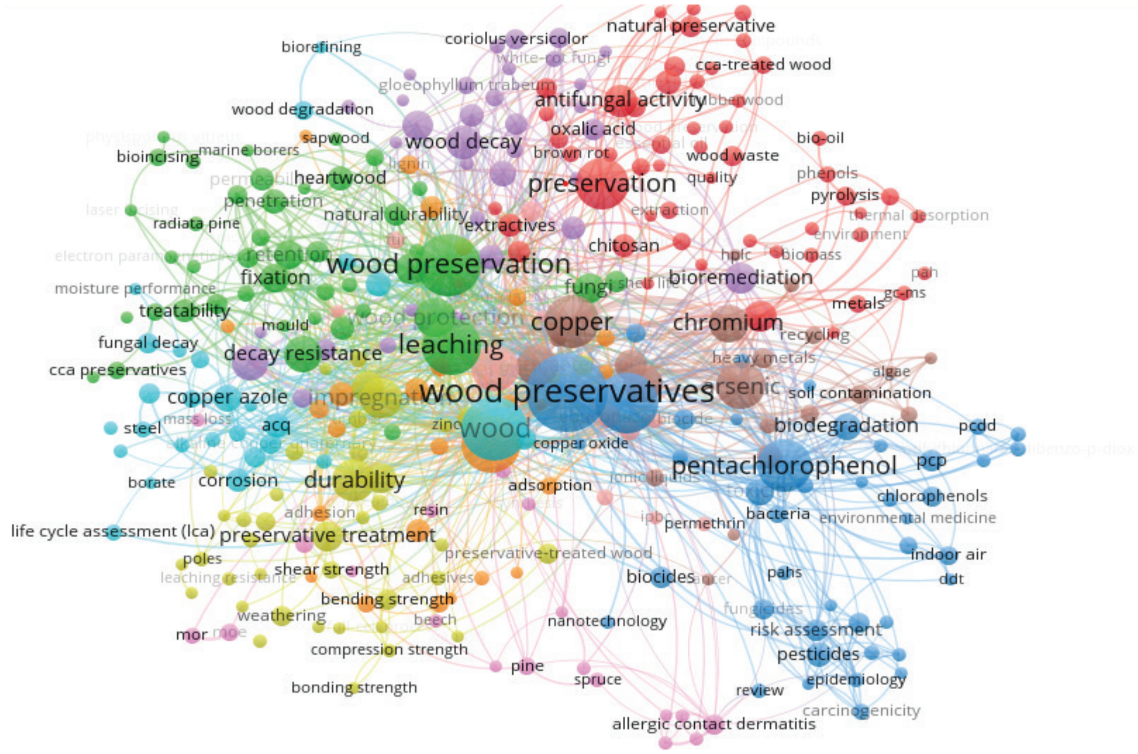

Figure 4. Network visualisation map of author's keywords.

Major Players and Research Collaborations

This section analysed the literature to answer the third research question, which aimed to assess international collaboration in the field of wood preservatives by looking at (a) publication counts by country, (b) the most prolific research institutions, (c) authorship patterns and (d) citation frequencies.

Publication by countries. *Figure 5* provides a summary of the publications on wood preservatives for the top 20 countries. There were 822 research publications in the USA on the topic of wood preservatives, followed by Germany (307), China (233) and Canada (218). Less than 200 publications were scattered over the globe, including Japan, the United Kingdom, Australia, Turkey, Brazil, India, Sweden, Finland, France, Poland, South Korea, Slovenia, New Zealand, Spain, Indonesia, Italy and Malaysia. Evidently, wood preservatives are essential across multiple continents, including North America, Europe, Asia, Oceania, and South America.

Although Canada ranked fourth in terms of total publications, it is imperative to emphasise that the country has higher total citations (n = 5,384) compared to Germany (n = 4,069) and China (n = 2,703) with higher total publications (*Figure 5*). The number of publications in Asia, including China, Japan, India, South Korea, Indonesia and Malaysia, was competitive, with China in the lead.

Main institutions. Analyses were conducted on the current status of the leading wood preservatives research centres. The top 20 most prolific institutions and their total number of publications are shown in *Table 5*. USA Forest Products Laboratory was ranked first in terms of publication volume, followed by Mississippi State University and Oregon State University. The top 10 institutes conducting wood preservatives research included five in the United States, two each in Canada, New Zealand, and Germany, as well as one each in Slovenia, Japan, Australia, Brazil, Hong Kong, China and Turkey.

Authorship analysis. In addition to analysing the current state of collaboration, this section also elucidated the most productive authors writing about wood preservatives. Twenty one of the prominent authors with at least 18 publications in the area of wood processing were Morrell, J J; Humar, M; Nicholas, D D; Cooper, P A; Zelinka, S L; Kartal, S N; Anon Schultz, TP; Pizzi, A; Imamura, Y; Pohleven, F; Ruddick, J N R; Barnes, H M; Militz, H; Kamdem, D P; Schwarze, F W M R.; Gjovik, L R; Lesar, B; Paes, J B; Clausen, C A and Tascioglu, C (*Table 6*). Six of the authors were from the United States, indicating that the country produced productive authors in the field of wood preservatives research. In terms of the number of total citations, Pizzi, A was rated first with 1,039 citations followed by Clausen, C A (774) and Nicholas, D D (733). There was a total of 154 authors contributing more than 3,719 articles on wood preservative.

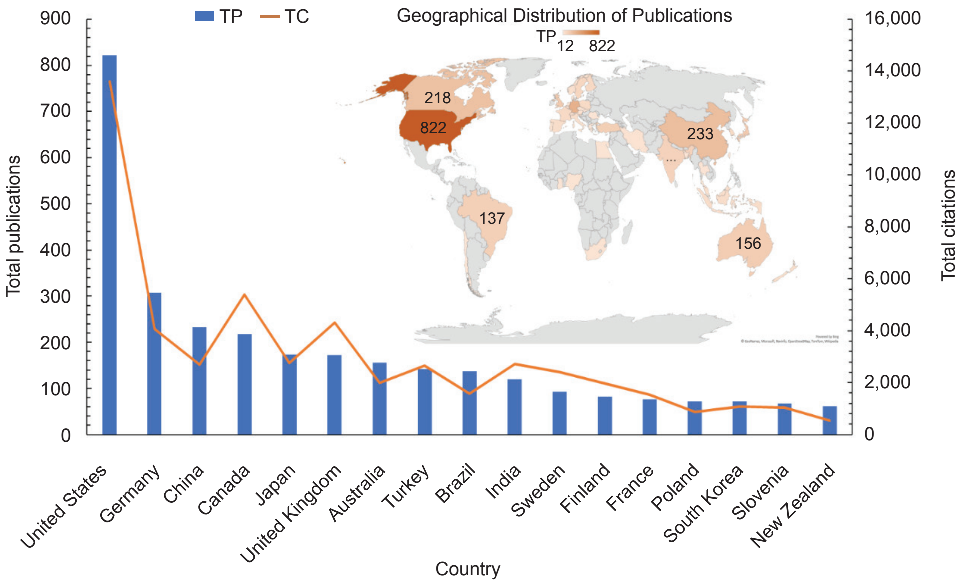

Figure 5. Total publications and total citations based on geographical location.

TABLE 5. MOST ACTIVE INSTITUTIONS

Institution	TP	%	Country	NCP	TC	C/P	C/CP	h	g
USDA Forest Products Laboratory	172	4.63	US	158	2,962	17.22	18.75	30	48
Mississippi State University	86	2.31	US	8	56	0.65	7.00	5	7
Oregon State University	85	2.29	US	9	80	0.94	8.89	6	8
USDA forest service	75	2.02	US	9	59	0.79	6.56	4	7
Univerza v Ljubljani	63	1.69	Slovenia	59	788	12.51	13.36	17	24
United States Department of Agriculture	50	1.35	US	44	767	15.34	17.43	15	26
Kyoto University	44	1.18	Japan	41	835	18.98	20.37	18	27
Commonwealth Scientific and Industrial Research Organization	44	1.18	Australia	42	442	10.05	10.52	12	19
The University of British Columbia	41	1.10	Canada	40	900	21.95	22.50	17	29
University of Toronto	41	1.10	Canada	39	465	11.34	11.92	13	18
SCION	38	1.02	New Zealand	31	321	8.45	10.35	10	17
Bundesforschungsanstalt fur Forst Und Holzwirtschaft	37	1.00	Germany	29	342	9.24	11.79	11	17
Federal Institute for Materials Research and Testing Berlin	37	1.00	Germany	31	286	7.73	9.23	8	15
Universidade de São Paulo	35	0.94	Brazil	28	240	6.86	8.57	8	14
University of Florida	34	0.91	Hong Kong	31	977	28.74	31.52	19	31
College of Forest Resources	34	0.91	New Zealand	31	543	15.97	17.52	12	22
Northeast Forestry University	33	0.89	China	24	192	5.82	8.00	9	12
Michigan State University	32	0.86	US	30	491	15.34	16.37	13	21
Sveriges lantbruksuniversitet	30	0.81	Sweden	30	658	21.93	21.93	15	25
Karadeniz Technical University	28	0.75	Turkey	26	824	29.43	31.69	17	26
Michigan Technological University	27	0.73	US	23	600	22.22	26.09	11	23

Note: TP - total number of publications; NCP - number of cited publications; TC - total citations; C/P - average citations per publication; C/CP - average citations per cited publication; h - h-index; g - g-index.

The current study employed VOSviewer for co-author analysis to further examine the authors' collaboration. The study was based on the fact that significant numbers of authors were cited at least once in a single article about wood preservatives and were calculated using the fractional counting method. Specific qualities such as colour, circle size, text size and thickness enhanced the writers' relationship. Associated authors were listed sequentially, as shown by the same colour. For example, the figure suggested that Nicholas, D D; Schultz, T P; Barnes, H M and Zelinka, S L; Xue, W; Kennepohl, P and Ruddick worked closely together. In addition, Nicholas, D D; Schultz, T P; Barnes, H M appeared to have had an equivalent strong collaboration with colleagues from other regions in the world, including Canada and Slovenia.

Figure 6 depicts the network visualisation map of the associated nation of the authors. Only countries with multiple articles cited were considered. The data suggested that the United States played a crucial role in international collaboration with tight connections to China, Japan and Germany; whereas Uruguay had links with Turkey, France and Japan. Next, the third research question emphasised the topic of citation.

Citation analysis. *Table 7* gives an overview of references to research on wood preservatives from the Scopus database. A total of 5,389 citations were recorded for 3,717 publications published during 115 years (1909-2024), which equates to an average of 485.87 citations per year.

Table 8 presents an overview of the 10 most often cited research articles on the subject of wood preservatives, ranked by the number of times each document was cited. "Wood Modification: Chemical, Thermal and Other Processes" by C.A.S. Hill was the most cited publication with 1,361 citations (Hill, 2006). The second and third publications, which were both released in 2011 and 2005, were research articles entitled "Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils," written by Ma *et al.* (2011) and totalling 776 citations while Holley and Patel (2005) articles entitled "Improvement of shelf-life and safety of perishable foods by plant essential oils and smoke antimicrobials" with 761 citations.

Sources Titles

Additionally, studies on wood preservatives have been published in a number of journals, conferences, and books. *Table 9* indicates that the most active source title was considered based on the total number of articles published under each source title. "Forest Products Journal" had the most significant (242) followed by "Holzforschung" (193). Although "International Biodeterioration and Biodegradation" had fewer total publications (n = 80), it proved to be one of the leaders in total citations (n = 2,057). Other top sources titles included Holz Als Roh Und Werkstoff, Bioresources, International Biodeterioration and Biodegradation, Wood Science and Technology, Chemosphere, Holz Als Roh Und Werkstoff European Journal of Wood and Wood Industries, Wood and Fiber Science, European Journal of Wood and Wood Products.

Figure 7 depicts a visualisation of a term co-occurrence network, based on the title and abstract fields, with at least 15 items. The width of the node shows the item's weight, while the thickness of the connecting line reflects the item's connection strength. When words are displayed in the same colour, they are more likely to appear together. Framework, efficacy, competency, substance, perspective, policy and implementation, for instance, were tightly related and regularly co-occur in the diagram, as were other terms represented in red.

In recent years, there has been a proliferation of research on wood preservatives, with WV serving as one of the bio-wood preservatives, across a wide range of disciplines. The research on oil palm WV, on the other hand, has only recently begun to emerge after making its debut in 2017 with one article and currently three articles in 2023. The purpose of this review was to integrate and assess all current studies, to explain the identified contradictions in the literature, and to provide directions for capacity-related subjects. The data indicated that research on the topic has increased in the past 18 years. More articles published showed that the research stream was not stagnant, as it followed a route of evaluation and incorporated new approaches.

Studies on WV and oil palm WV are currently taking place not just in North America, China and Indonesia but also in many other parts of the world due to their special qualities, and they have been translated into more than 20 different languages. Thus, a 115- year bibliometric analysis of the Scopus-indexed literature on wood preservatives published from 1909 to 17 March 2023 was conducted.

The data collected in response to these inquiries was analysed using several key frameworks. In response to the first research question, two studies found that in 1909, publications on wood preservatives began, and by 1912, "A new wood preservative" was published in Industrial and Engineering Chemistry. For WV, the studies began in 1949 with 'On the Utilisation of Furfural obtained from Cooking of Bamboo stalks with

TABLE 6. AUTHORSHIP ANALYSIS

Author name	TP	%	Affiliation	Country	NCP	TC	C/P	C/CP	h	g
Morrell, J. J.	77	2.07	University of the Sunshine Coast, Sippy Downs, Australia	Australia	66	418	5.43	6.33	11	15
Humar, M.	55	1.48	Univerza v Ljubljani, Department of Wood Science and Technology, Ljubljana, Slovenia	Slovenia	51	594	10.80	11.65	15	21
Nicholas, D. D.	37	1.00	Mississippi State University, Department of Sustainable Bioproducts, Mississippi State, United States	United States	34	733	19.81	21.56	12	26
Cooper, P. A.	35	0.94	University of Toronto, Faculty of Forestry, Toronto, Canada	Canada	34	359	10.26	10.56	12	16
Zelinka, S. L.	30	0.81	USDA Forest Products Laboratory, Building and Fire Sciences, Madison, United States	United States	23	287	9.57	12.48	11	16
Kartal, S. N.	29	0.78	Istanbul University-Cerrahpasa, Istanbul, Turkey	Turkey	28	654	22.55	23.36	14	25
Anon	27	0.73	No affiliation available	-	2	7	0.26	3.50	1	2
Schultz, T. P.	27	0.73	Silvaware, Inc., Starkville, United States	United States	25	642	23.78	25.68	12	25
Pizzi, A.	26	0.70	Université de Lorraine, Nancy, France	France	25	1,039	38.48	41.56	18	25
Imamura, Y.	23	0.62	Research Institute for Sustainable Humanosphere, Uji, Japan	Japan	22	467	20.30	21.23	12	21
Pohleven, F.	23	0.62	Univerza v Ljubljani, Department of Wood Science and Technology, Ljubljana, Slovenia	Slovenia	23	425	18.48	18.48	12	20
Ruddick, J. N. R.	23	0.62	Mychem Wood Protection Consultants Ltd., Vancouver, Canada	Canada	21	228	9.91	10.86	10	14
Barnes, H. M.	22	0.59	College of Forest Resources, College of Forest Resources, Mississippi State, United States	United States	19	278	12.64	14.63	7	16
Militz, H.	22	0.59	Georg-August-Universität Göttingen, Gottingen, Germany	Germany	19	543	24.68	28.58	10	19
Kamdem, D. P.	20	0.54	Michigan State University, East Lansing, United States	United States	18	195	9.75	10.83	9	13
Schwarze, F. W. M. R.	20	0.54	EMPA - Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Cellulose & Wood Materials, Dubendorf, Switzerland	Switzerland	19	431	21.55	22.68	12	19
Gjovik, L. R.	19	0.51	USDA Forest Products Laboratory, Madison, United States	United States	8	35	1.84	4.38	3	5
Lesar, B.	19	0.51	Univerza v Ljubljani, Department of Wood Science and Technology, Ljubljana, Slovenia	Slovenia	17	200	10.53	11.76	8	13
Paes, J. B.	19	0.51	Federal University of Espirito Santo, Vitória, Brazil	Brazil	15	138	7.26	9.20	6	11
Clausen, C. A.	18	0.48	USDA Forest Service, Washington, D.C., United States	United States	18	744	41.33	41.33	12	18
Tascioglu, C.	18	0.48	Düzce Üniversitesi, Department of Forest Products Engineering, Duzce, Turkey	Turkey	18	422	23.44	23.44	11	18

Note: TP - total number of publications; NCP - number of cited publications; TC - total citations; C/P - average citations per publication; C/CP - average citations per cited publication; h - h-index; g - g-index.

TABLE 7. WOOD PRESERVATIVES RESEARCH CITATIONS METRICS

Item	Metric
Total articles	3,717
Total citations	55,389
Number of years	115
Citations per year	485.87
Citations per articles	14.9
Authors per articles	3.29
h-index	84
g-index	142

TABLE 8. MOST CITED PUBLICATIONS

No.	Authors	Title	Year	TC	C/Y
1	Hill, C. A. S. (Hill, 2006)	Wood modification: Chemical, thermal and other processes	2006	1,362	80.12
2.	Ma, Y., Prasad, M. N. V., Rajkumar, M., Freitas, H. (Ma *et al*., 2011)	Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils	2011	776	64.67
3	Holley, R. A., Patel, D. (Holley & Patel, 2005)	Improvement of shelf-life and safety of perishable foods by plant essential oils and smoke antimicrobials	2005	761	42.28
4	Pointing, S. B. (Pointing, 2001)	Feasibility of bioremediation by white-rot fungi	2001	698	31.73
5	Baldrian, P. (Baldrian, 2003)	Interactions of heavy metals with white-rot fungi	2003	555	27.75
6	Sophia A., C., Lima, E. C. (Sophia A & Lima, 2018)	Removal of emerging contaminants from the environment by adsorption	2018	512	102.4
7	Barceloux, D. G. (Barceloux, 1999)	Chromium	1999	505	21.04
8	Wang, S., Mulligan, C. N. (Wang & Mulligan, 2006)	Occurrence of arsenic contamination in Canada: Sources, behaviour and distribution	2006	485	28.53
9	Seidler, A., Hellenbrand, W., Robra, B. P., Vieregge, P., Nischan, P., Joerg, J., Oertel, W. H., Ulm, G., Schneider, E. (Seidler *et al*., 1996)	Possible environmental, occupational and other etiologic factors for Parkinson's disease: A case-control study in Germany	1996	403	14.93
10	Hingston, J. A., Collins, C. D., Murphy, R. J., Lester, J. N. (Hingston *et al*., 2001)	Leaching of chromated copper arsenate wood preservatives: A review	2001	293	13.32

Note: TC - total citations; C/Y - citations per year.

TABLE 9. MOST ACTIVE SOURCE TITLES

Sources title	TP	TC
Forest Products Journal	242	2,610
Holzforschung	193	2,966
Holz Als Roh Und Werkstoff	104	749
Bioresources	84	1,043
International Biodeterioration and Biodegradation	80	2,057
Wood Science and Technology	68	1,230
Chemosphere	54	1,491
Holz Als Roh Und Werkstoff European Journal of Wood and Wood Industries	47	171
Wood and Fibre Science	45	465
European Journal of Wood and Wood Products	44	515

Note: TP - total number of publications; TC - total citations.

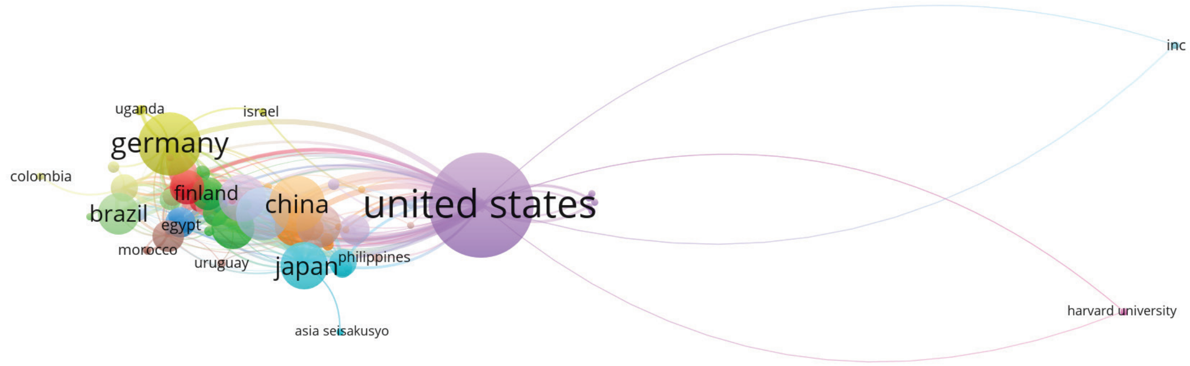

Figure 6. Network visualisation map of the co-authors by country for wood preservatives research.

Wood Vinegar' published in Nihon Ringakkai Shi/ Journal of the Japanese Forestry Society and 'On the pulp-making process of bamboo by the wood vinegar and paper-making tests of these pulps in The Journal of the Japanese Forestry Society. The studies on oil palm WV were only conducted in a few nations which included Indonesia, Malaysia, Ghana, Japan and Thailand, because these nations are the main producers of palm oil. In addition, Japan has a comprehensive plan for the utilisation of biomass for energy production through its Biomass Nippon Plan Policy, which was adopted in 2002 and encompasses the use of palm kernel shells (PKS). Moreover, Japan also has numerous research collaborations with South East Asian countries (Pambudi *et al.*, 2017). The first article published in 2017 appeared in the Indian Journal of Experimental Biology, entitled 'Optimisation of pyroligneous acid production from palm kernel shell and its potential antibacterial and antibiofilm activities'.

From 1968 to 2018, the number of articles on wood preservatives and WV has steadily increased. The growth may be attributable to the publication entitled "The chemical analysis of copper, chromium, and arsenic preservative-treated wood" which detailed the introduction of chemical controls such as copper, chromium and arsenic as wood preservatives. This revealed that experts from the United States recognised wood preservatives early on in their development. In contrast, the increasing interest in WV can be traced back to a study published in 2018 entitled "Combining biochar, zeolite, and wood vinegar for composting of pig manure: The effect on greenhouse gas emission and nitrogen conservation". This study examined the impact of varying concentrations of WV, mixed with biochar and zeolite, on GHG emissions, nitrogen loss and compost maturity, which is increasingly important as the need for sustainable development goals (SDG). Despite the late start of research into oil palm WV, an article entitled "Antifungal and antitermitic activities of wood vinegar from oil palm trunk" (Oramahi *et al.*, 2018) received the most citations in 2018 (46). This demonstrates that interest in oil palm WV is encouraging given that eliminating biological damage is one of the key objectives of the wood protection industry and oil palm WV has benefits as a low-impact technology.

More than 60 articles were published in 1996, probably because wood preservatives began to attract significant attention outside the United States. It was first available in European countries such as Germany, Austria, Sweden, Finland and the United Kingdom. However, there was a significant decrease in overall citations between 2021 and 2022 (from 1,279 to 203). The decrease could be attributed to the rise in publications that focused on environmentally friendly and sustainable wood preservation methods. Compared to other forms of literature, wood preservatives, WV and oil palm WV were most frequently discovered in journal articles. Top-ranking journals from prominent English-language publishers, including Forest Products Society, Springer Nature, North Carolina University, Walter de Gruyter and Elsevier, published the three most popular source titles. All of these publishers had a distinguished history and track record in the publishing industry. The wood preservatives documentations were likewise mostly written in English, despite being also published in other languages.

This article aimed to clarify the most often discussed wood preservatives topics among academics. From the VOSviewer results, it is possible to see the conclusions from the analysis of the keywords, titles, and abstracts. The most common keywords used by researchers were "wood preservation," "wood," "wood preservatives," "wood protection," and "antifungal activity," which denoted the primary subject areas. These terminologies were closely related to one another in the field of wood protectives, showing that they served a vital purpose and might act as a solid starting point for more investigations in this field.

Figure 7. VOSviewer visualisation of a term co-occurrence network based on title and abstract fields.

Wood preservation being the main keyword, is consistent with other findings in this study, such as the most cited articles (*Table 8*) and the most active source titles (*Table 9*). These publications were on wood degradation, wood treated with chemicals like zinc oxide, and the removal of pollutants such as copper, chromium, and arsenic from CCA treated wood.

Chemicals assessment was, in fact, the most frequently cited source in wood preservatives study. This may help other researchers determine the prevalent keyword in the wood preservatives study, which corresponds to the significance of this topic in the wood preservatives domain. In response to the third research question, an examination of countries, institutions, authors, and citations suggested that there was a reasonable amount of scientific collaboration on wood preservatives research worldwide. Although the wood preservatives industry was established in the United States, scientific articles have been widely spread in South America, Europe, Oceania and Asia. Consequently, despite its beginnings in the United States, the framework has global applicability. This study found that most papers on wood preservatives were published in the United States, indicating that it was at the forefront of wood preservatives research at the time. This may be because the United States began research and publication on wood preservatives in 1913. In addition, the majority were in English, German, Chinese, Portuguese, Japanese, Korean, Spanish and French. Based on the variety of languages used and the situations in which they were employed, it was anticipated that the publication rate would also increase. The reputations of the three American institutions including among the most active research institutions in the field of wood preservatives were also indicated.

Wood treatment is the main focus of wood preservatives after an extensive analysis of the industry's major players, including leading researchers and institutions. Publications on wood treatment generated a lot of attention and citations from other academics, and their impact has grown. It is necessary to analyse research collaboration to comprehend how academics work together. This can give insight into clustered research among authors from a given region, which can subsequently be used to rationalise and stimulate new researchers among authors from deprived areas. This study could determine the countries with the most active research collaborations through co-authorship analyses. These included the United States, India, Australia, South Korea, Japan, and Indonesia. However, collaboration in wood preservatives research across Africa was limited.

CONCLUSION

Study on wood preservatives was analysed in terms of its publication history, citation structure, and central themes, and recommendations for future studies are provided. The increase in the number of publications outside the United States, such as in Europe, Oceania and Asia, indicated that researches on wood preservatives were widely spread and had a substantial effect. A bibliometric approach was used in this study to present the data obtained from the Scopus database, which included quantity, quality, and structural map (*i.e.*, the number of publications by year, document types, languages, keyword analysis, most active source titles, countries with the most contributions towards wood preservatives research, most active institutions, number of citations and citation metrics). It should be noted that the research was restricted to the Scopus database and was based on the desired keywords used in the titles of the documents. Other significant and comprehensive databases that covered wood preservatives, such as the Web of Science, Google Scholar, and EBSCO Hosts, were not taken into account in this study. Thus, the overall results of the wood preservatives publishing patterns could be limited. In the future, researchers may use a variety of databases to search, sift through, and compare search results using a variety of keyword terms to determine how research on wood preservatives varied by study theme. This study summarises the current state of knowledge on wood preservatives and provides information on rising journal performance trends, collaborative patterns, and research features that support in understanding. Each characteristic contributed to the expansion of this field of study, which could result in new possibilities for expanding wood technology systems. In addition, this will aid young researchers in gaining a wider view of this topic. This study contributes further by applying the bibliometric method to enhance academics' understanding of the literature on wood preservatives. The bibliometric method will continue to be a vital tool for detecting gaps in any subject or field. As a result, researchers can employ the method when reviewing literature on a particular subject. The results of this study will help researchers comprehend the reasons behind the widespread use of wood preservatives in the fields of materials science, agriculture, and biological science. They will also provide ideas for further research. Due to its widespread use in wood treatment across the globe and that it is now well-liked among European nations like Germany, Sweden, Finland, France, Poland, Slovenia, Spain, and Italy, which are actively producing publications related to wood preservatives, wood preservatives are predicted to continue to be relevant for the next 10 years. This shows that its appeal is expanding and that it is being used more frequently globally.

ACKNOWLEDGEMENT

The authors thank the Director-General of MPOB for permission to publish this work.

REFERENCES

Adhikari, S., & Ozarska, B. (2018). Minimizing environmental impacts of timber products through the production process "From Sawmill to Final Products." *Environmental Systems Research*, *7*(1). https://doi.org/10.1186/s40068-018-0109-x

Aguayo, M. G., Erazo, O., Montero, C., Reyes, L., Gacitúa, W., Gómez, L., & Torres, H. (2022). Analyses of impregnation quality and mechanical properties of radiata pine wood treated with copper nanoparticle- and micronized-copper-based wood preservatives. *Forests*, *13*(10), 1636. https://doi.org/10.3390/f13101636

Ahmed, S., Fatima, R., & Hassan, B. (2020). Evaluation of different plant derived oils as wood preservatives against subterranean termite *Odontotermes obesus*. *Maderas. Ciencia Y Tecnología*, *22*(1), 109–120.

Ariffin, S. J., Yahayu, M., El-Enshasy, H., Malek, R. A., Aziz, A. A., Hashim, N. M., & Zakaria, Z. A. (2017). Optimization of pyroligneous acid production from palm kernel shell and its potential antibacterial and antibiofilm activities. *Indian Journal of Experimental Biology*, *55*(7), 427–435.

Bahmani, M., & Schmidt, O. (2018). Plant essential oils for environment-friendly protection of wood objects against fungi. *Maderas, Ciencia Y Tecnología*, *20*(3), 325–332.

Baldrian, P. (2003). Interactions of heavy metals with white-rot fungi. *Enzyme and Microbial Technology*, *32*(1), 78–91. https://doi.org/10.1016/s0141-0229(02)00245-4

Barbero-López, A., Akkanen, J., Lappalainen, R., Peräniemi, S., & Haapala, A. (2020). Bio-based wood preservatives: Their efficiency, leaching and ecotoxicity compared to a commercial wood preservative. *The Science of the Total Environment*, *753*, 142013. https://doi.org/10.1016/j.scitotenv.2020.142013

Barceloux, D. G. (1999). Chromium. *Journal of Toxicology Clinical Toxicology*, *37*(2), 173–194. https://doi.org/10.1081/clt-100102418

Bayatkashkoli, A., Kameshki, B., Ravan, S., & Shamsian, M. (2017). Comparing of performance of treated particleboard with alkaline copper quat, boron-fluorine-chromium-arsenic and Chlorotalonil against *Microcerotermes diversus* and *Anacanthotermes vagans* termite. *International Biodeterioration & Biodegradation*, *120*, 186–191. https://doi.org/10.1016/j.ibiod.2017.03.003

Bernard Effah, S. A. G. A. (2015). Safety measures in wood processing: An important component for the entrepreneur – The case of a local furniture industry in Ghana. *International Journal of Innovative Research in Science Engineering and Technology*, *04*(05), 2677–2686. https://doi.org/10.15680/ijirset.2015.0405004

Broda, M. (2020). Natural compounds for wood protection against fungi – A review. *Molecules*, *25*(15), 3538. https://doi.org/10.3390/molecules25153538

Cai, L., Lim, H., Kim, Y., & Jeremic, D. (2020). β-Cyclodextrin-allyl isothiocyanate complex as a natural preservative for strand-based wood composites. *Composites Part B Engineering*, *193*, 108037. https://doi.org/10.1016/j.compositesb.2020.108037

Calegari, E. P., Porto, J. S., Nejeliski, D. M., Da Cunha Duarte, L., & De Oliveira, B. F. (2017). Experimental study on waterproofing MDF with castor oil-based vegetal polyurethane. *Matéria (Rio De Janeiro)*, *22*(3). https://doi.org/10.1590/s1517-707620170003.0211

Chang, H., Tu, K., Wang, X., and Liu, J. (2015). Facile preparation of stable superhydrophobic coatings on wood surfaces using silica-polymer nanocomposites. *BioResources. 10*(2), 2585-2596.

Chen, C., Chen, J., Zhang, S., Cao, J., & Wang, W. (2020). Forming textured hydrophobic surface coatings via mixed wax emulsion impregnation and drying of poplar wood. *Wood Science and Technology*, *54*(2), 421–439. https://doi.org/10.1007/s00226-020-01156-7

Desvita, H., Faisal, M., Mahidin, N., & Suhendrayatna, N. (2022). Antimicrobial potential of wood vinegar from cocoa pod shells (*Theobroma cacao* L.) against *Candida albicans* and *Aspergillus niger*. *Materials Today Proceedings*, *63*, S210–S213. https://doi.org/10.1016/j.matpr.2022.02.410

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Engwall, M. A., Pignatello, J. J., & Grasso, D. (1999). Degradation and detoxification of the wood preservatives creosote and pentachlorophenol in water by the photo-Fenton reaction. *Water Research*, *33*(5), 1151–1158. https://doi.org/10.1016/s0043-1354(98)00323-6

Freeman, M. H., Shupe, T. F., Vlosky, R. P., & Barnes, H. M. (2003). Past, present, and future of the wood preservation industry. *Forest Products Journal*, *53*(10), 8–15.

Hill, C. A. S. (2006). *Wood modification: Chemical, thermal and other processes*. John Wiley and Sons, Ltd.

Hingston, J., Collins, C., Murphy, R., & Lester, J. (2001). Leaching of chromated copper arsenate wood preservatives: A review. *Environmental Pollution*, *111*(1), 53–66. https://doi.org/10.1016/s0269-7491(00)00030-0

Holley, R. A., & Patel, D. (2005). Improvement in shelf-life and safety of perishable foods by plant essential oils and smoke antimicrobials. *Food Microbiology*, *22*(4), 273–292. https://doi.org/10.1016/j.fm.2004.08.006

Jin, W., Pastor-Pérez, L., Yu, J., Odriozola, J., Gu, S., & Reina, T. (2020). Cost-effective routes for catalytic biomass upgrading. *Current Opinion in Green and Sustainable Chemistry*, *23*, 1–9. https://doi.org/10.1016/j.cogsc.2019.12.008

Jung, M., Hong, J., Lee, K., Jo, C., Kim, Y., & Choi, J. (2016). Fungal inhibitory effect of *Pinus densiflora* and *Zelkova serrata* woods with wood-vinegar. *Journal of Korea Technical Association of the Pulp and Paper Industry*, *48*(5), 13–21. https://doi.org/10.7584/jktappi.2016.10.48.5.13

Khademibami, L., & Bobadilha, G. S. (2022). Recent developments studies on wood protection research in academia: A review. *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.793177

Lazim, A. M., Azfaralariff, A., Azman, I., Arip, M. N. M., Zubairi, S., Kaus, N. M., Nazir, N., Mohamad, M., Kamil, A., Azzahari, A. D., Abdullah, A., & Ariff, A. Z. (2020). Improving wood durability against *G. Trabeum* and *C. versicolor* using starch based antifungal coating from *Dioscorea hispida* sp. *Journal of the Taiwan Institute of Chemical Engineers*, *115*, 242–250. https://doi.org/10.1016/j.jtice.2020.10.002

Lebow, S., Brooks, K., & Simonsen, J. (2002). *Environmental impact of treated wood in service*. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. https://www.fpl.fs.usda.gov/documnts/pdf2002/lebow02a.pdf

Lee, C. L., Chin, K. L., Khoo, P. S., Hafizuddin, M. S., & H'ng, P. S. (2022). Production and potential application of pyroligneous acids from rubberwood and oil palm trunk as wood preservatives through vacuum-pressure impregnation treatment. *Polymers*, *14*(18), 3863. https://doi.org/10.3390/polym14183863

Lee, S. H., Zaidon, A., Rasdianah, D., Lum, W. C., & Aisyah, H. A. (2020). Alteration in colour and fungal resistance of thermally treated oil palm trunk and rubberwood particleboard using palm oil. *Journal of Oil Palm Research, 32*(1), 83–89. https://doi.org/10.21894/jopr.2020.0009

Li, T., Cui, L., Song, X., Cui, X., Wei, Y., Tang, L., Mu, Y., & Xu, Z. (2022). Wood decay fungi: An analysis of worldwide research. *Journal of Soils* *and Sediments*, *22*(6), 1688–1702. https://doi.org/10.1007/s11368-022-03225-9

Lin, L., Chen, Y., Wang, S., & Tsai, M. (2009). Leachability, metal corrosion, and termite resistance of wood treated with copper-based preservative. *International Biodeterioration & Biodegradation*, *63*(4), 533–538. https://doi.org/10.1016/j.ibiod.2008.07.012

Liu, X., Zhan, Y., Li, X., Li, Y., Feng, X., Bagavathiannan, M., Zhang, C., Qu, M., & Yu, J. (2021). The use of wood vinegar as a non-synthetic herbicide for control of broadleaf weeds. *Industrial Crops and Products*, *173*, 114105. https://doi.org/10.1016/j.indcrop.2021.114105

Ma, Y., Prasad, M., Rajkumar, M., & Freitas, H. (2011). Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. *Biotechnology Advances*, *29*(2), 248–258. https://doi.org/10.1016/j.biotechadv.2010.12.001

Maier, D. (2021). Building materials made of wood waste a solution to achieve the sustainable development goals. *Materials*, *14*(24), 7638. https://doi.org/10.3390/ma14247638

Mansour, A. Z., Ahmi, A., Popoola, O. M. J., & Znaimat, A. (2022). Discovering the global landscape of fraud detection studies: A bibliometric review. *Journal of Financial Crime*, *29*(2), 701–720. https://doi.org/10.1108/jfc-03-2021-0052

Martín, J. A., & López, R. (2023). Biological deterioration and natural durability of wood in Europe. *Forests*, *14*(2), 283. https://doi.org/10.3390/f14020283

Meena, R. K. (2022). Hazardous effect of chemical wood preservatives on environmental conditions, ecological biodiversity and human being and its alternatives through different botanicals: A review. *Environment and Ecology*, *40*(3), 1137–1143.

Mohamad Amini, M. H. M., Hashim, R., & Sulaiman, N. S. (2019). Formaldehyde-free wood composite fabricated using oil palm starch modified with glutardialdehyde as the binder. *International Journal of Chemical Engineering*, *2019*, 1–9. https://doi.org/10.1155/2019/5357890

Moral-Muñoz, J. A., Herrera-Viedma, E., Santisteban-Espejo, A., & Cobo, M. J. (2020). Software tools for conducting bibliometric analysis in science: An up-to-date review. *El Profesional De La Informacion*, *29*(1). https://doi.org/10.3145/epi.2020.ene.03

Muhuri, P. K., Shukla, A. K., & Abraham, A. (2019). Industry 4.0: A bibliometric analysis and detailed overview. *Engineering Applications of Artificial Intelligence*, *78*, 218–235. https://doi.org/10.1016/j.engappai.2018.11.007

Nadali, E., Tajvidi, M., & Naghdi, R. (2021). Effects of fungal biodegradation on structure-property relationships of medium density fibre board and hybrid polypropylene composite made from sugar-cane residue. *International Wood Products Journal*, *12*(3), 152–163. https://doi.org/10.1080/20426445.2021.1910169

Nordin, N., Khatibi, A., & Azam, S. M. F. (2022). Nonprofit capacity and social performance: Mapping the field and future directions. *Management Review Quarterly*, *74*(1), 171–225. https://doi.org/10.1007/s11301-022-00297-2

Oramahi, H. A., Wardoyo, E. R. P., & Kustiati, N. (2019). Optimization of pyrolysis condition for bioactive compounds of wood vinegar from oil palm empty bunches using response surface methodology (RSM). *IOP Conference Series Materials Science and Engineering*, *633*(1), 012058. https://doi.org/10.1088/1757-899x/633/1/012058

Oramahi, H. A., Yoshimura, T., Diba, F., Setyawati, D., & Nurhaida, N. (2018). Antifungal and antitermitic activities of wood vinegar from oil palm trunk. *Journal of Wood Science*, *64*(3), 311–317. https://doi.org/10.1007/s10086-018-1703-2

Pambudi, N. A., Itaoka, K., Chapman, A., Hoa, N. D., & Yamakawa, N. (2017). Biomass energy in Japan: Current status and future potential. *International Journal of Smart Grid and Clean Energy*, *6*(2), 119–126. https://doi.org/10.12720/sgce.6.2.119-126

Pařil, P., Baar, J., Čermák, P., Rademacher, P., Prucek, R., Sivera, M., & Panáček, A. (2017). Antifungal effects of copper and silver nanoparticles against white and brown-rot fungi. *Journal of Materials Science*, *52*(5), 2720–2729. https://doi.org/10.1007/s10853-016-0565-5

Pędzik, M., Janiszewska, D., & Rogoziński, T. (2021). Alternative lignocellulosic raw materials in particleboard production: A review. *Industrial Crops and Products*, *174*, 114162. https://doi.org/10.1016/j.indcrop.2021.114162

Petrič, M., Murphy, R. J., & Morris, I. (2000). Microdistribution of some copper and zinc containing waterborne and organic solvent wood preservatives in spruce wood cell walls. *Holzforschung*, *54*(1), 23–26. https://doi.org/10.1515/hf.2000.004

Pointing, S. B. (2001). Feasibility of bioremediation by white-rot fungi. *Applied Microbiology and Biotechnology*, *57*(1–2), 20–33. https://doi.org/10.1007/s002530100745

Pour, M. F., Mehdinia, M., Kiamahalleh, M. V., Hoseini, K. D., Hatefnia, H., & Dorieh, A. (2021). Biological durability of particleboard: Fungicidal properties of Ag and Cu nanoparticles against *Trametes versicolor* white-rot fungus. *Wood Material Science and Engineering*, *17*(6), 929–936. https://doi.org/10.1080/17480272.2021.1977996

Sandberg, D., Kutnar, A., & Mantanis, G. (2017). Wood modification technologies – A review. *iForest – Biogeosciences and Forestry*, *10*(6), 895–908. https://doi.org/10.3832/ifor2380-010

Seidler, A., Hellenbrand, W., Robra, B., Vieregge, P., Nischan, P., Joerg, J., Oertel, W. H., Ulm, G., & Schneider, E. (1996). Possible environmental, occupational, and other etiologic factors for Parkinson's disease. *Neurology*, *46*(5), 1275. https://doi.org/10.1212/wnl.46.5.1275

Smith, S. T. (2020). Water-borne wood preservation and end-of-life removal history and projection. *Engineering*, *12*(02), 117–139. https://doi.org/10.4236/eng.2020.122011

Sophia, A. C., & Lima, E. C. (2018). Removal of emerging contaminants from the environment by adsorption. *Ecotoxicology and Environmental Safety*, *150*, 1–17. https://doi.org/10.1016/j.ecoenv.2017.12.026

Sun, W., Tajvidi, M., Hunt, C. G., Cole, B. J., Howell, C., Gardner, D. J., & Wang, J. (2022). Fungal and enzymatic pretreatments in hot-pressed lignocellulosic bio-composites: A critical review. *Journal of Cleaner Production*, *353*, 131659. https://doi.org/10.1016/j.jclepro.2022.131659

Teaca, C.-A., Roşu, D., Mustaţă, F., Rusu, T., Roşu, L., Roşca, I., & Varganici, C. D. (2019). Natural bio-based products for wood coating and protection against degradation: A Review. *BioResources*, *14*(2), 4873–4901.

Teng, T.-J., Mat Arip, M. N., Sudesh, K., Nemoikina, A., Jalaludin, Z., Ng, E.-P., & Lee, H.-L. (2018). Conventional technology and nanotechnology in wood preservation: A Review. *BioResources*, *13*(4), 9220–9252.

The Business Research Company. (2022). *Wood products global market report 2022*. Retrieved June 9, 2023, from https://www.thebusinessresearchcompany.com/report/wood-products-market

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Wang, S., & Mulligan, C. N. (2006). Occurrence of arsenic contamination in Canada: Sources, behavior and distribution. *The Science of the Total Environment*, *366*(2–3), 701–721. https://doi.org/10.1016/j.scitotenv.2005.09.005

Yan, L., Zeng, F., Chen, Z., Chen, S., & Lei, Y. (2020). Improvement of wood decay resistance by salicylic acid/silica microcapsule: Effects on the salicylic leaching, microscopic structure and decay resistance. *International Biodeterioration & Biodegradation*, *156*, 105134. https://doi.org/10.1016/j.ibiod.2020.105134

Zhang, F., Shao, J., Yang, H., Guo, D., Chen, Z., Zhang, S., & Chen, H. (2019). Effects of biomass pyrolysis derived wood vinegar on microbial activity and communities of activated sludge. *Bioresource Technology*, *279*, 252–261. https://doi.org/10.1016/j.biortech.2019.01.133

Zhang, W., Sun, H., Zhu, C., Wan, K., Zhang, Y., Fang, Z., & Ai, Z. (2018). Mechanical and water-resistant properties of rice straw fiberboard bonded with chemically-modified soy protein adhesive. *RSC Advances*, *8*(27), 15188–15195. https://doi.org/10.1039/c7ra12875d